US010718163B2

(12) United States Patent
Gilbrech

(10) Patent No.: US 10,718,163 B2
(45) Date of Patent: Jul. 21, 2020

(54) **PULSE TRANSFORMER FOR DOWNHOLE ELECTROCRUSHING DRILLING**

(71) Applicants: **Halliburton Energy Services, Inc.**, Houston, TX (US); **Chevron U.S.A. Inc.**, San Ramon, CA (US); **SDG LLC**, Minden, NV (US)

(72) Inventor: **Joshua A. Gilbrech**, Albuquerque, NM (US)

(73) Assignees: **Halliburton Energy Services, Inc.**, Houston, TX (US); **Chevron U.S.A. Inc.**, San Ramon, CA (US); **SDG LLC**, Minden, NV (US)

( * ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 251 days.

(21) Appl. No.: **15/750,406**

(22) PCT Filed: **Apr. 3, 2017**

(86) PCT No.: **PCT/US2017/025751**
§ 371 (c)(1),
(2) Date: **Feb. 5, 2018**

(87) PCT Pub. No.: **WO2018/186828**
PCT Pub. Date: **Oct. 11, 2018**

(65) **Prior Publication Data**

US 2018/0313158 A1 Nov. 1, 2018

(51) **Int. Cl.**
***E21B 7/15*** (2006.01)
***E21C 37/18*** (2006.01)
***E21B 10/00*** (2006.01)

(52) **U.S. Cl.**
CPC ................ ***E21B 7/15*** (2013.01); ***E21B 10/00*** (2013.01); ***E21C 37/18*** (2013.01)

(58) **Field of Classification Search**
CPC ............................... E21B 7/15; E21B 41/0085
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,835,785 A * 5/1958 Williams ................. B23H 1/00 219/69.18
2,930,137 A * 3/1960 Arps ....................... E21B 47/02 33/312

(Continued)

FOREIGN PATENT DOCUMENTS

WO 2013/070609 5/2013
WO 2015/124733 8/2015

OTHER PUBLICATIONS

International Preliminary Report on Patentability for PCT Patent Application No. PCT/US2017/025751, dated Oct. 17, 2019; 11 pages.

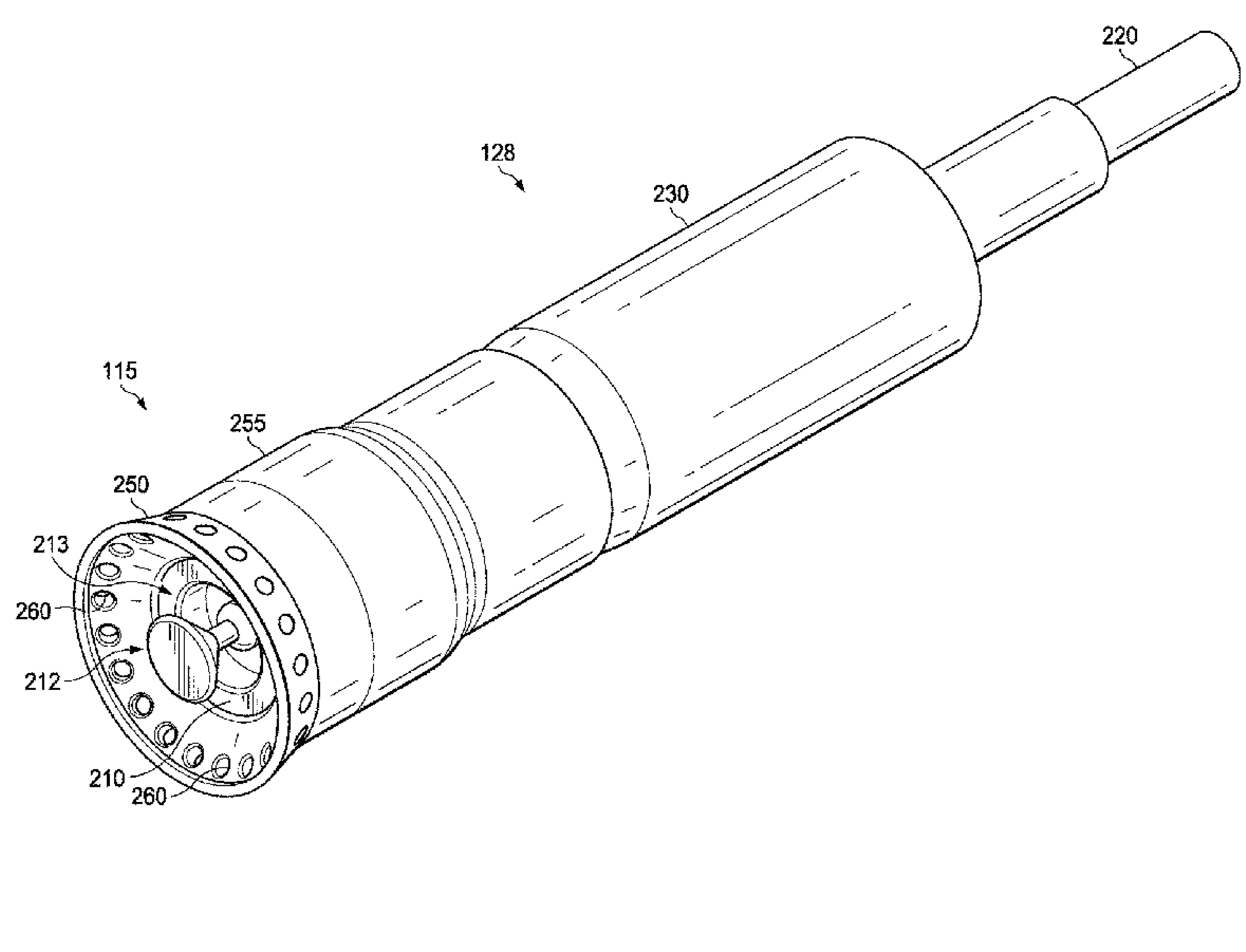
(Continued)

*Primary Examiner* — Shane Bomar
(74) *Attorney, Agent, or Firm* — Baker Botts L.L.P.

(57) **ABSTRACT**

A downhole drilling system is disclosed. The downhole drilling system may include a pulse-generating circuit electrically coupled to a power source configured to provide an alternating current at a frequency and an input voltage, the pulse-generating circuit comprising an input stage circuit electrically coupled to the power source, the input stage circuit configured to control the alternating current in the pulse-generating circuit; a transformer circuit electrically coupled to the input stage circuit, the transformer circuit comprising an open-core transformer configured to generate an output voltage higher than the input voltage; and an output stage circuit electrically coupled to the transformer circuit, the output stage circuit configured to store energy for an electric pulse; and a drill bit including a first electrode and a second electrode electrically coupled to the output stage circuit to receive the electric pulse from the pulse-generating circuit.

**21 Claims, 7 Drawing Sheets**



(56) **References Cited**

U.S. PATENT DOCUMENTS

| | | | | |
|---|---|---|---|---|
| 3,071,690 | A * | 1/1963 | Fearon | G01V 5/107 376/118 |
| 3,142,029 | A * | 7/1964 | Keen, Jr. | H01F 27/2847 336/84 R |
| 3,387,203 | A * | 6/1968 | Munnelly | H03B 19/03 363/171 |
| 3,489,970 | A * | 1/1970 | Wanlass | H03K 17/82 334/12 |
| 4,343,356 | A * | 8/1982 | Riggs | E21B 36/04 166/248 |
| 6,104,707 | A | 8/2000 | Abraham | |
| 7,394,226 | B1 | 7/2008 | Adler | |
| 10,113,364 | B2 * | 10/2018 | Moeny | E21B 7/15 |
| 2001/0022540 | A1 * | 9/2001 | Hill | H03C 3/16 332/102 |
| 2010/0224356 | A1 | 9/2010 | Moore | |
| 2012/0168177 | A1 * | 7/2012 | Moeny | E21B 7/15 166/380 |
| 2012/0235829 | A1 * | 9/2012 | Adnan | E21B 41/00 340/854.9 |
| 2013/0071286 | A1 * | 3/2013 | Watson | A61M 16/12 422/22 |
| 2013/0081874 | A1 | 4/2013 | Gutsol | |
| 2013/0140086 | A1 | 6/2013 | Moeny | |
| 2014/0008073 | A1 * | 1/2014 | Rey-Bethbeder | E21B 36/04 166/308.1 |
| 2014/0008968 | A1 * | 1/2014 | Moeny | E21B 7/15 307/2 |
| 2016/0017663 | A1 * | 1/2016 | Moeny | E21B 7/15 175/327 |
| 2017/0067292 | A1 | 3/2017 | Bayol et al. | |
| 2017/0350197 | A1 * | 12/2017 | Sugiura | E21B 47/12 |
| 2018/0053973 | A1 * | 2/2018 | Tong | G01R 33/3456 |

OTHER PUBLICATIONS

Examination Report for GCC Patent Application No. 2018-34995, dated Oct. 23, 2019; 4 pages.

International Search Report and Written Opinion for PCT Patent Application No. PCT/US2017/025751, dated Nov. 20, 2017; 17 pages.

O'Loughlin, J.P.; Sidler, J.D.; Rohwein, G.J., "Air core pulse transformer design," in Power Modulator Symposium, 1988. IEEE Conference Record of the 1988 Eighteenth , vol., No., pp. 325-330, Jun. 20-22, 1988; 6 pages.

Rohwein, G. J., et al. "An scr-switched, high voltage, high gain linear transformer system." Pulsed Power Conference, 1989. 7th. IEEE, 1989.; 4 pages.

Lawson, R.N.; Rohwein, G.J., "A study of compact, lightweight, high voltage inductors with partial magnetic cores," in Pulsed Power Conference, 1989. 7th , vol., No., pp. 906-908, 1989; 3 pages.

G. J. Rohwein, "A low-impedance, high-voltage direct drive transformer system," Power Modulator Symposium, 1988. IEEE Conference Record of the 1988 Eighteenth. Hilton Head, SC, 1988, pp. 331-335; 5 pages.

Shotts, Zac, et al. "Design Methodology for Dual Resonance Pulse Transformers." Pulsed Power Conference, 2005 IEEE. IEEE, 2005; 4 pages.

Uglum, J.R. "Theory of the Resonant Transformer Accelerator and some Design Considerations." Energy Sciences Inc., Aug. 1973; 42 pages.

"Dupont Kapton: Summary of Properties." Retrieved from url: http://www.dupont.com/content/dam/dupont/products-and-services/membranes-and-films/polyimde-films/documents/DEC-Kapton-summary-of-properties.pdf, 2017; 20 pages.

Lim, Soo Won, et al. "Fabrication and operation testing of a dual resonance pulse transformer for PFL pulse charging." Journal of the Korean Physical Society 59.61 (2011): 3679-3682; 4 pages.

Lawson, R. N., and G. J. Rohwein. *Partial core pulse transformer*. U.S. Pat. No. 7,764,253. Sandia National Labs., Albuquerque, NM (United States), 1991.

Adler, R. J., and V. M. Weeks. "Design and operation of a 700 kV arbitrary waveform generator." *Pulsed Power Conference, 2009. PPC'09. IEEE*. IEEE, 2009.

* cited by examiner

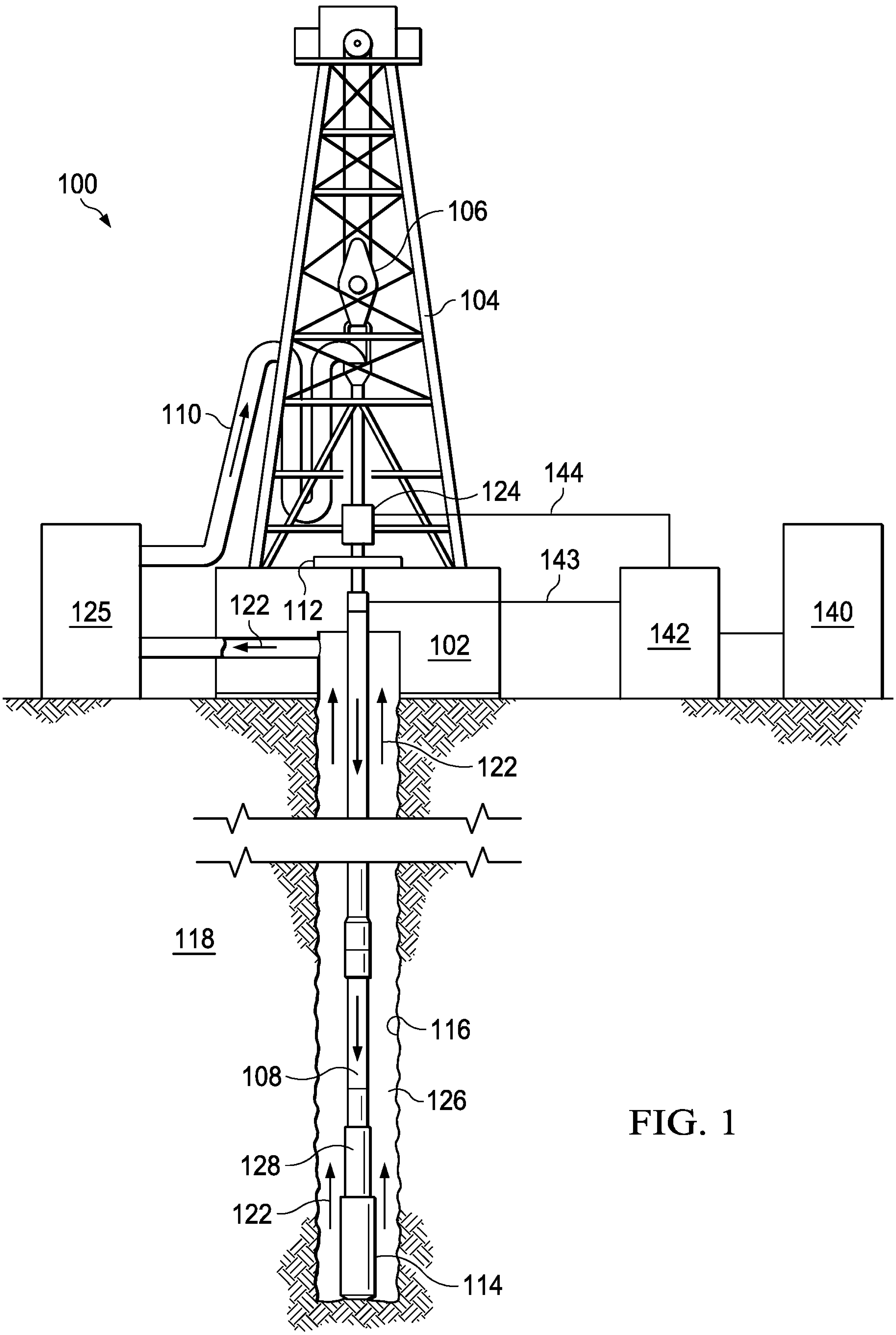

100
106
104
110
144
124
143
112
122
125
102
142
140
122
118
116
108
126
128
122
114

FIG. 1

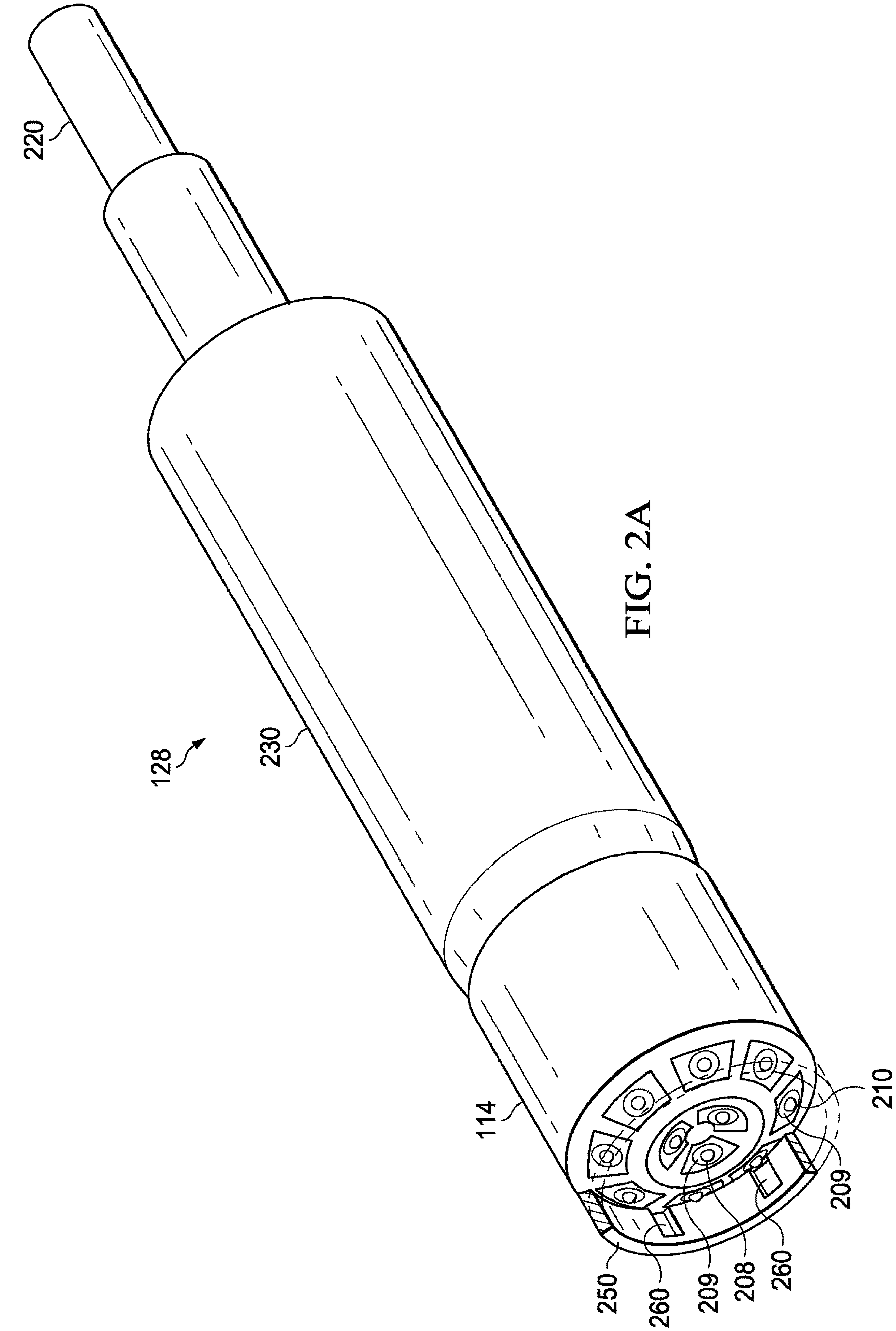



FIG. 2A

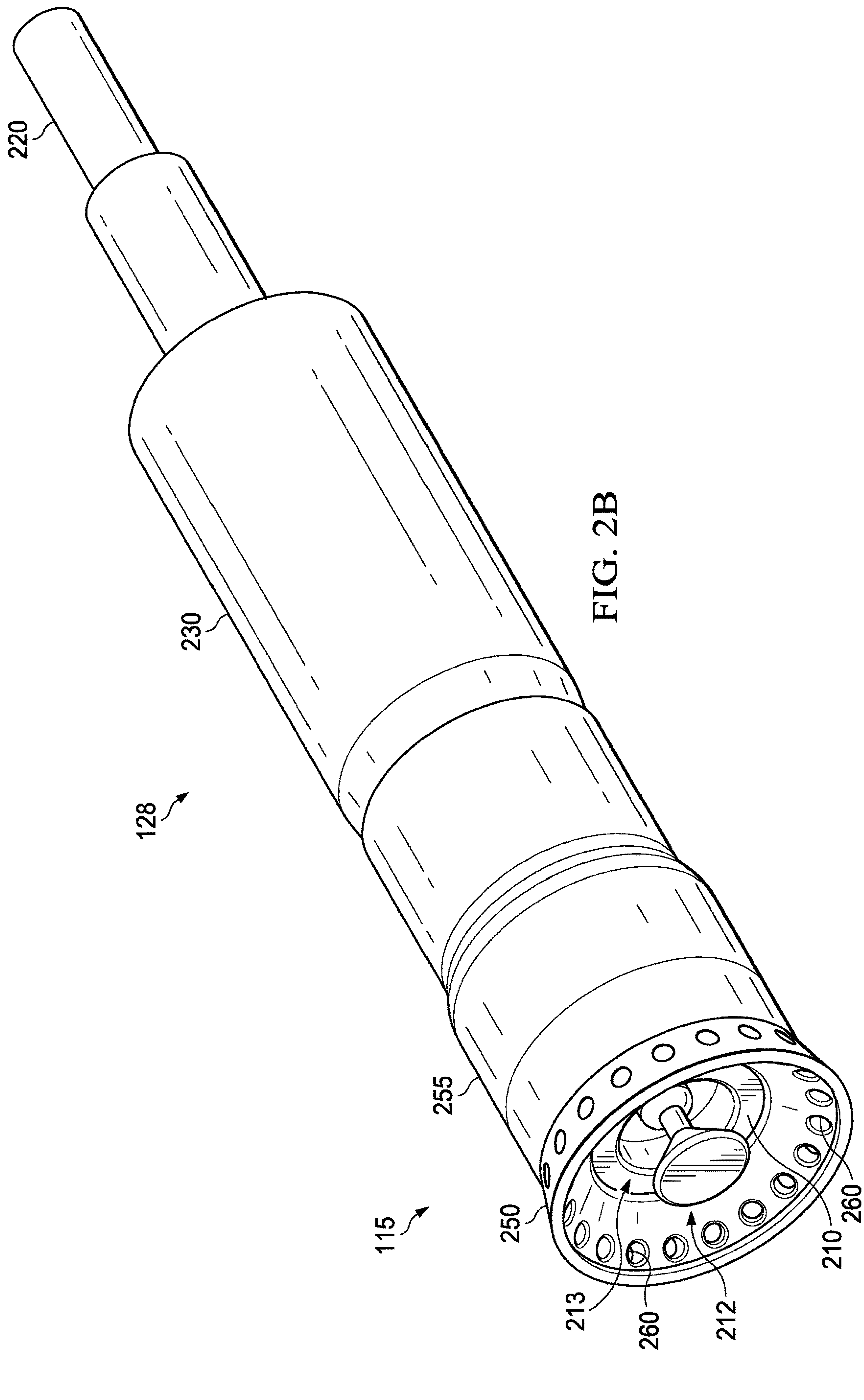



FIG. 2B

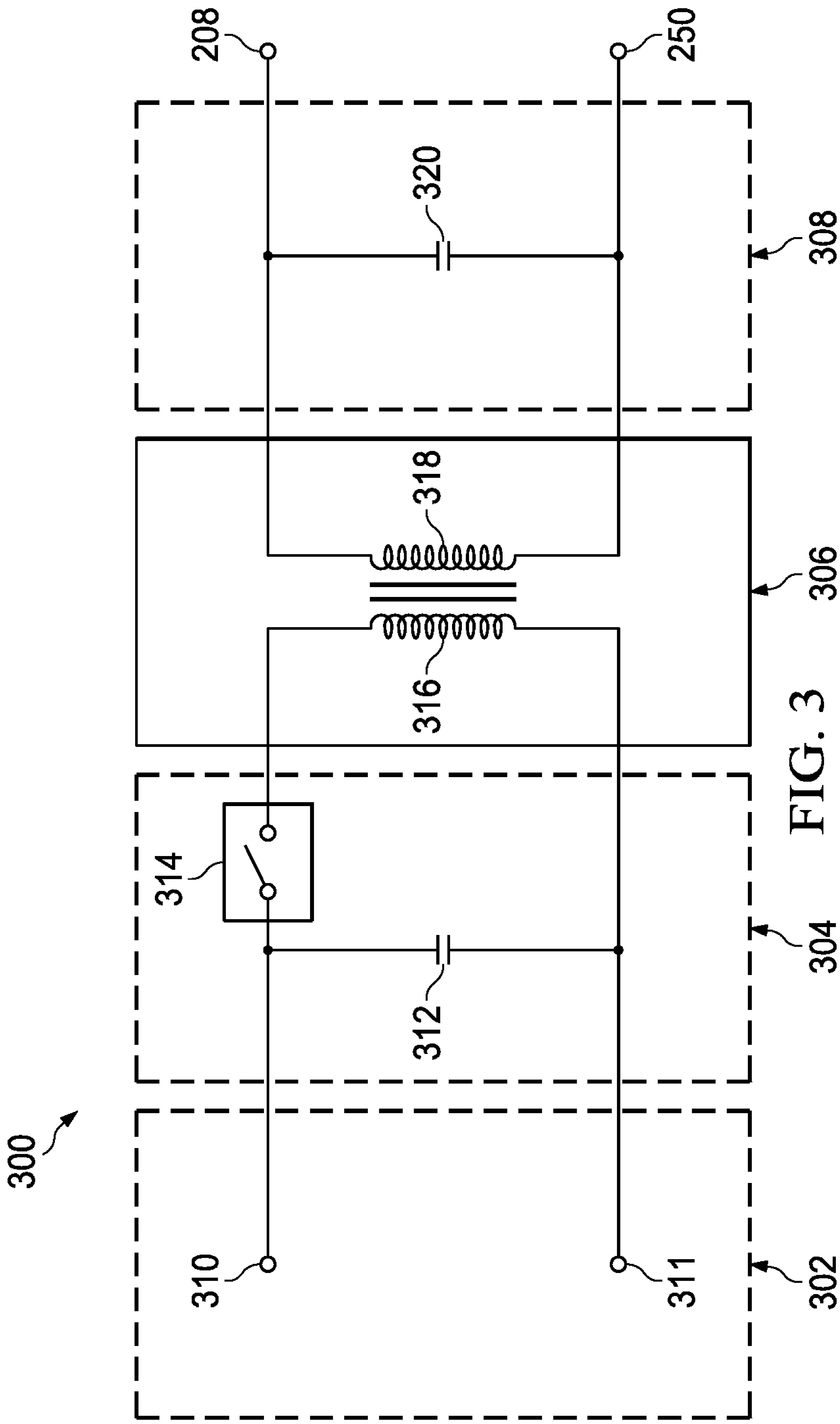



FIG. 3

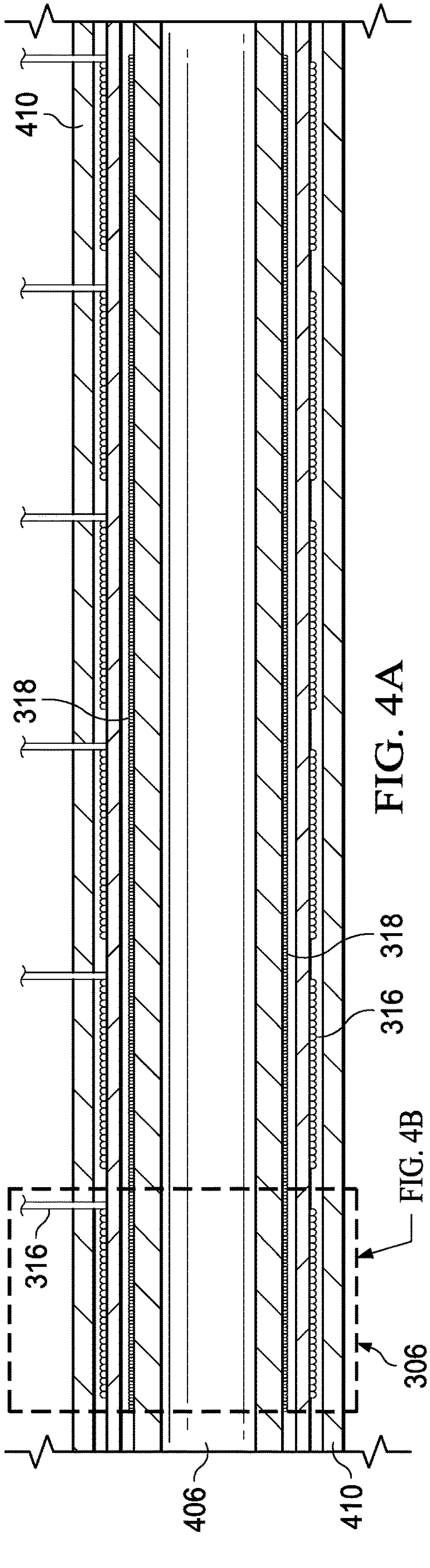

410
318
318
316
316
306
FIG. 4B
406
410

FIG. 4A

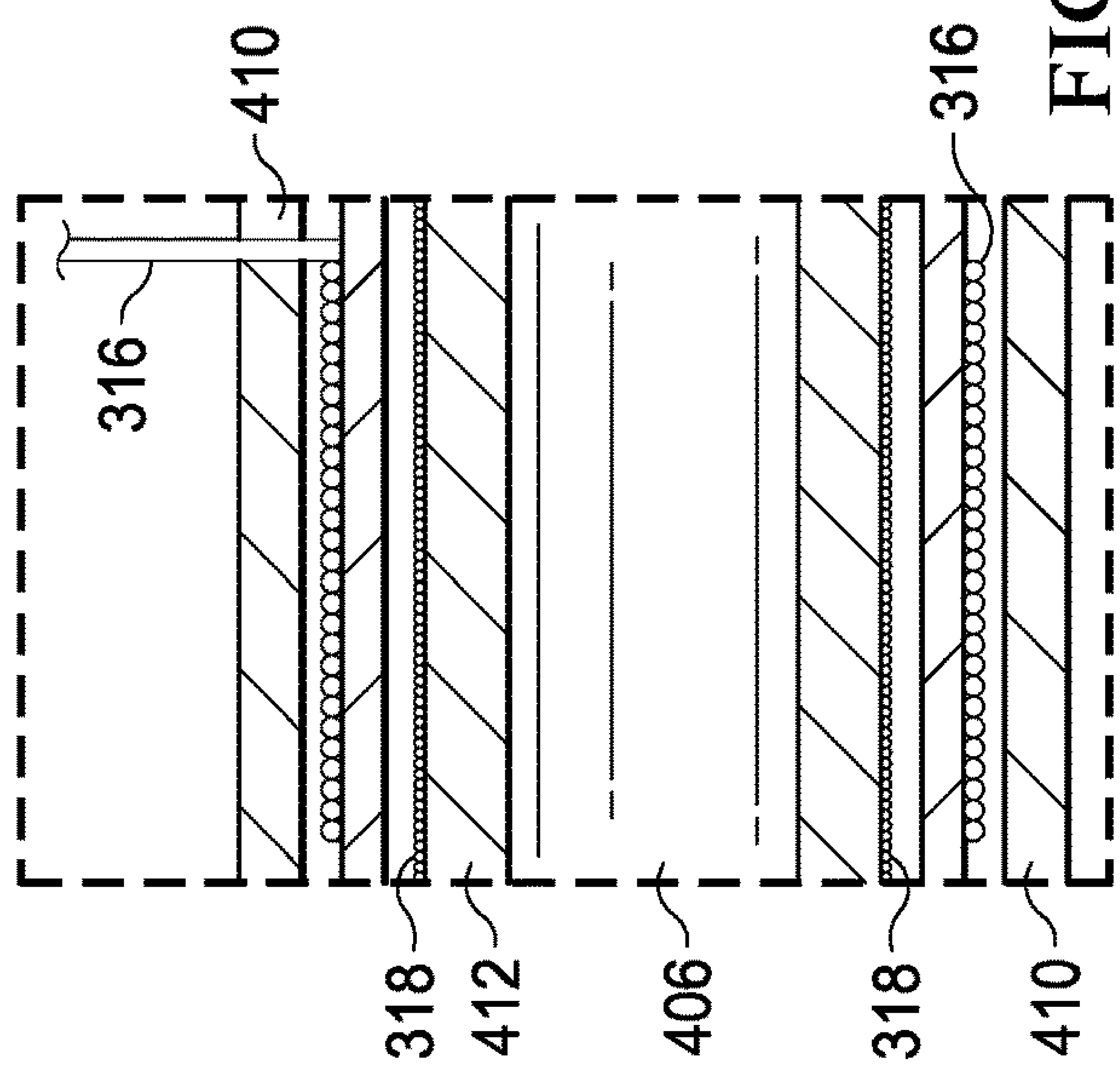

410
316
316
318
412
406
318
410

FIG. 4B

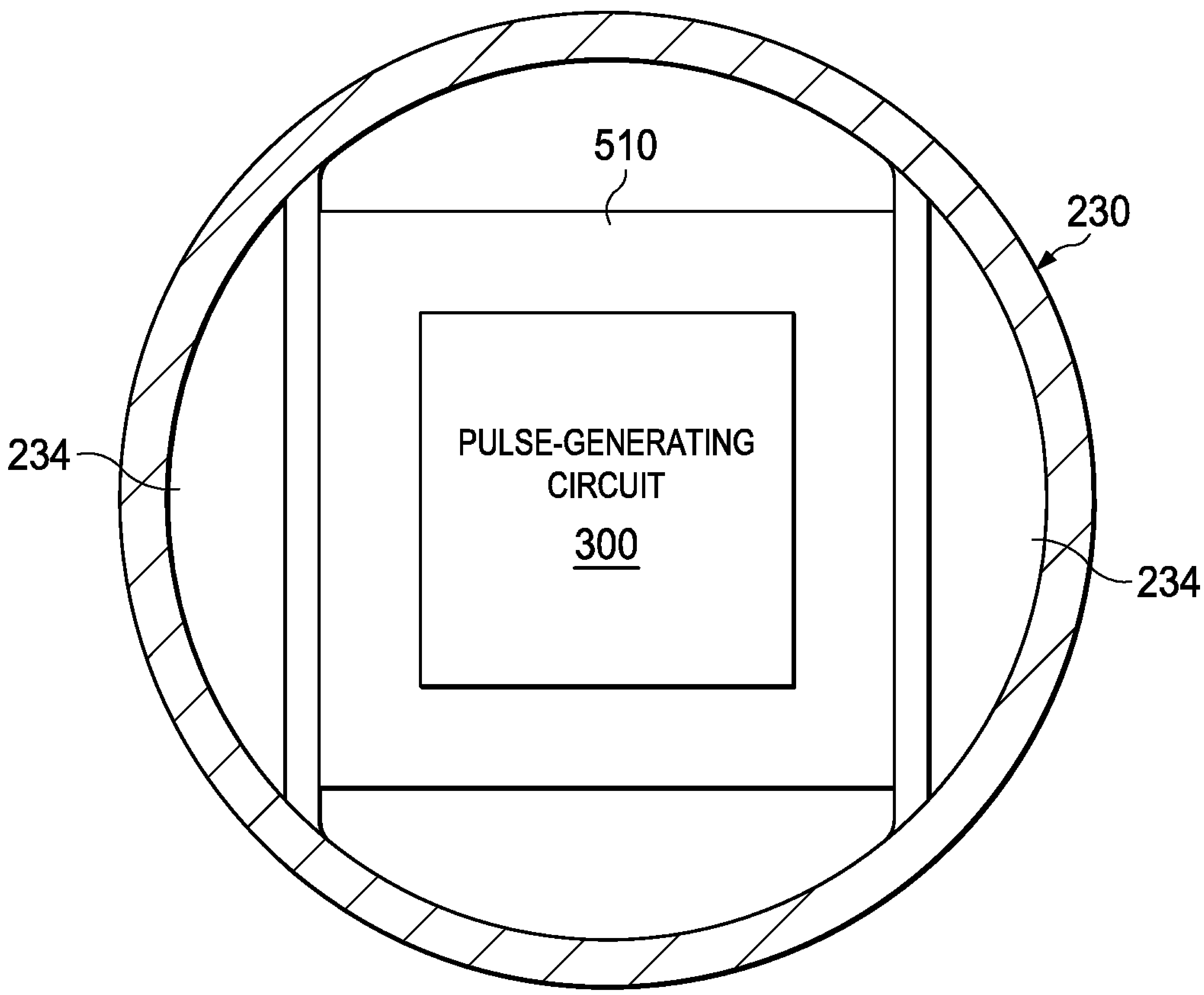



FIG. 5

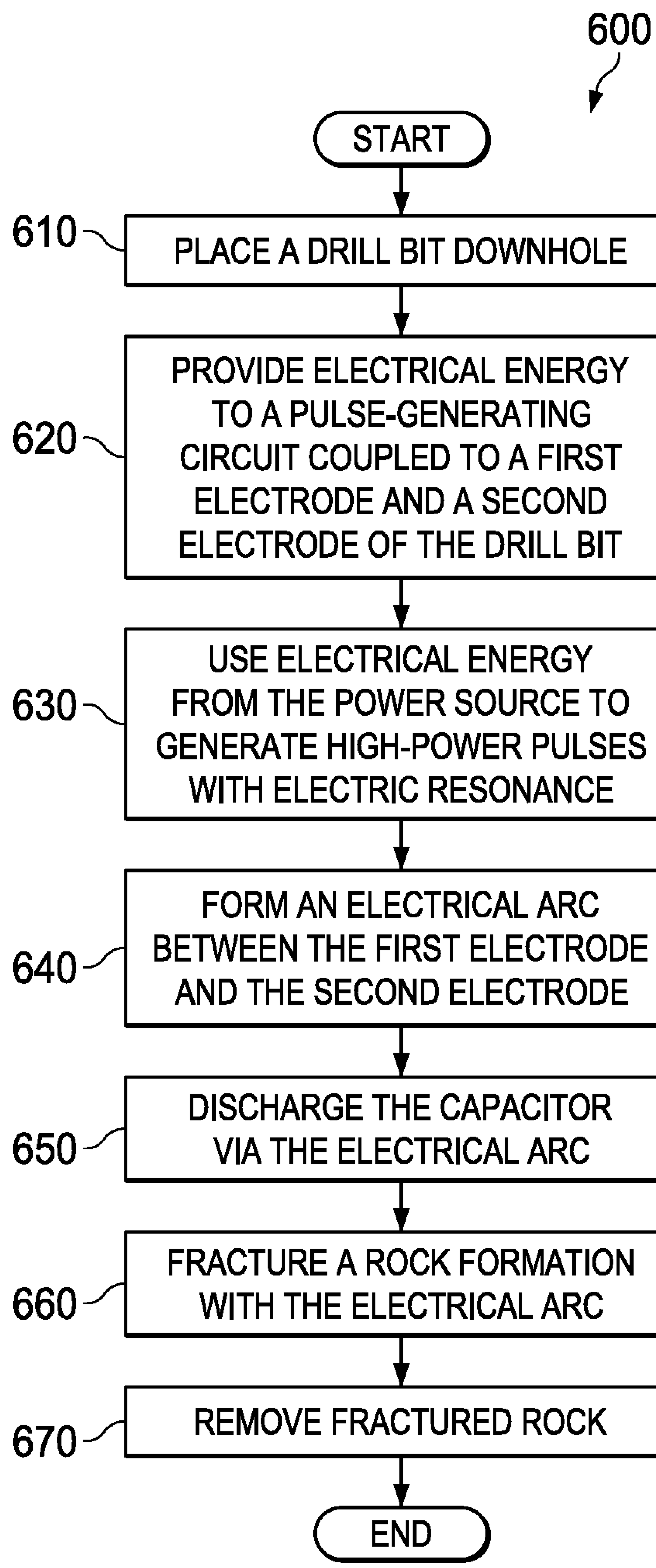

600
START
610
PLACE A DRILL BIT DOWNHOLE
620
PROVIDE ELECTRICAL ENERGY TO A PULSE-GENERATING CIRCUIT COUPLED TO A FIRST ELECTRODE AND A SECOND ELECTRODE OF THE DRILL BIT
630
USE ELECTRICAL ENERGY FROM THE POWER SOURCE TO GENERATE HIGH-POWER PULSES WITH ELECTRIC RESONANCE
640
FORM AN ELECTRICAL ARC BETWEEN THE FIRST ELECTRODE AND THE SECOND ELECTRODE
650
DISCHARGE THE CAPACITOR VIA THE ELECTRICAL ARC
660
FRACTURE A ROCK FORMATION WITH THE ELECTRICAL ARC
670
REMOVE FRACTURED ROCK
END

FIG. 6

# PULSE TRANSFORMER FOR DOWNHOLE ELECTROCRUSHING DRILLING

## RELATED APPLICATIONS

This application is a U.S. National Stage Application of International Application No. PCT/US2017/025751 filed Apr. 3, 2017, which designates the United States, and which is incorporated herein by reference in its entirety.

## TECHNICAL FIELD

The present disclosure relates generally to downhole electrocrushing drilling and, more particularly, to pulse transformers for downhole electrocrushing drilling.

## BACKGROUND

Electrocrushing drilling uses pulsed power technology to drill a wellbore in a rock formation. Pulsed power technology repeatedly applies a high electric potential across the electrodes of an electrocrushing drill bit, which ultimately causes the surrounding rock to fracture. The fractured rock is carried away from the bit by drilling fluid and the bit advances downhole.

## BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present disclosure and its features and advantages, reference is now made to the following description, taken in conjunction with the accompanying drawings, in which:

FIG. **1** is an elevation view of an exemplary downhole electrocrushing drilling system used in a wellbore environment;

FIG. **2**A is a perspective view of exemplary components of a bottom-hole assembly for a downhole electrocrushing drilling system;

FIG. **2**B is a perspective view of exemplary components of a bottom-hole assembly for a downhole electrocrushing drilling system;

FIG. **3** is a schematic for an exemplary pulse-generating circuit for a downhole electrocrushing drilling system;

FIG. **4**A is a side cross-sectional view of an exemplary transformer circuit for a downhole electrocrushing drilling system;

FIG. **4**B is an exploded view of an exemplary transformer circuit for a downhole electrocrushing drilling system

FIG. **5** is a top cross-sectional view of an exemplary pulsed-power tool for a downhole electrocrushing drilling system; and

FIG. **6** is a flow chart of exemplary method for drilling a wellbore.

## DETAILED DESCRIPTION

Electrocrushing drilling may be used to form wellbores in subterranean rock formations for recovering hydrocarbons, such as oil and gas, from these formations. Electrocrushing drilling uses pulsed-power technology to repeatedly fracture the rock formation by repeatedly delivering high-energy electrical pulses to the rock formation. In some applications, certain components of a pulsed-power system may be located downhole. For example, a pulse-generating circuit may be located in a bottom-hole assembly (BHA) near the electrocrushing drill bit. The pulse-generating circuit may include a transformer that steps up a low-voltage power



source input into a high-voltage output that is used to generate electric pulses for powering electrodes of an electrocrushing drill bit. In addition, the pulse-generating circuit may be designed to withstand the harsh environment of a downhole pulsed-power system. For example, the pulse-generating circuit may operate over a wide temperature range (for example, from approximately 10 to 200 degrees Centigrade), and may physically withstand the vibration and mechanical shock resulting from the fracturing of rock during downhole electrocrushing drilling.

There are numerous ways in which a pulse-generating circuit may be implemented in a downhole electrocrushing pulsed-power system. Thus, embodiments of the present disclosure and its advantages are best understood by referring to FIGS. **1** through **6**, where like numbers are used to indicate like and corresponding parts.

FIG. **1** is an elevation view of an exemplary electrocrushing drilling system used to form a wellbore in a subterranean formation. Although FIG. **1** shows land-based equipment, downhole tools incorporating teachings of the present disclosure may be satisfactorily used with equipment located on offshore platforms, drill ships, semi-submersibles, and drilling barges (not expressly shown in FIG. **1**). Additionally, while wellbore **116** is shown as being a generally vertical wellbore, wellbore **116** may be any orientation including generally horizontal, multilateral, or directional.

Drilling system **100** includes drilling platform **102** that supports derrick **104** having traveling block **106** for raising and lowering drill string **108**. Drilling system **100** also includes pump **125**, which circulates electrocrushing drilling fluid **122** through a feed pipe to kelly **110**, which in turn conveys electrocrushing drilling fluid **122** downhole through interior channels of drill string **108** and through one or more orifices in electrocrushing drill bit **114**. Electrocrushing drilling fluid **122** then circulates back to the surface via annulus **126** formed between drill string **108** and the sidewalls of wellbore **116**. Fractured portions of the formation are carried to the surface by electrocrushing drilling fluid **122** to remove those fractured portions from wellbore **116**.

Electrocrushing drill bit **114** is attached to the distal end of drill string **108**. Power to electrocrushing drill bit **114** may be supplied from the surface. For example, generator **140** may generate electrical power and provide that power to power-conditioning unit **142**. Power-conditioning unit **142** may then transmit electrical energy downhole via surface cable **143** and a sub-surface cable (not expressly shown in FIG. **1**) contained within drill string **108** or attached to the side of drill string **108**. A pulse-generating circuit within BHA **128** may receive the electrical energy from power-conditioning unit **142**, and may generate high-energy pulses to drive electrocrushing drill bit **114**. The pulse-generating circuit may include an open-core, multi-segmented transformer as described in further detail below with reference to FIGS. **3**-**6**.

The pulse-generating circuit within BHA **128** may be utilized to repeatedly apply a high electric potential, for example at least 50 kilovolts (kV) or between approximately 50 kV and 200 kV, across the electrodes of electrocrushing drill bit **114**. Each application of electric potential is referred to as a pulse. When the electric potential across the electrodes of electrocrushing drill bit **114** is increased enough during a pulse to generate a sufficiently high electric field, an electrical arc forms through a rock formation at the bottom of wellbore **116**. The arc temporarily forms an electrical coupling between the electrodes of electrocrushing drill bit **114**, allowing electric current to flow through the arc inside a portion of the rock formation at the bottom of wellbore

116. The arc greatly increases the temperature and pressure of the portion of the rock formation through which the arc flows and the surrounding formation and materials. The temperature and pressure is sufficiently high to break the rock into small bits or cuttings. This fractured rock is removed, typically by electrocrushing drilling fluid **122**, which moves the fractured rock away from the electrodes and uphole. The terms "uphole" and "downhole" may be used to describe the location of various components of drilling system **100** relative to the bottom or end of wellbore **116** shown in FIG. **1**. For example, a first component described as uphole from a second component may be further away from the end of wellbore **116** than the second component. Similarly, a first component described as being downhole from a second component may be located closer to the end of wellbore **116** than the second component.

As electrocrushing drill bit **114** repeatedly fractures the rock formation and electrocrushing drilling fluid **122** moves the fractured rock uphole, wellbore **116**, which penetrates various subterranean rock formations **118**, is created. Wellbore **116** may be any hole drilled into a subterranean formation or series of subterranean formations for the purpose of exploration or extraction of natural resources such as, for example, hydrocarbons, or for the purpose of injection of fluids such as, for example, water, wastewater, brine, or water mixed with other fluids. Additionally, wellbore **116** may be any hole drilled into a subterranean formation or series of subterranean formations for the purpose of geothermal power generation.

Although drilling system **100** is described herein as utilizing electrocrushing drill bit **114**, drilling system **100** may also utilize an electrohydraulic drill bit. An electrohydraulic drill bit may have one or more electrodes and electrode spacing configurations similar to electrocrushing drill bit **114**. But, rather than generating an arc within the rock, an electrohydraulic drill bit applies a large electrical potential across the one or more electrodes and the ground ring to form an arc across the drilling fluid proximate the bottom of wellbore **116**. The high temperature of the arc vaporizes the portion of the fluid immediately surrounding the arc, which in turn generates a high-energy shock wave in the remaining fluid. The one or more electrodes of electrohydraulic drill bit may be oriented such that the shock wave generated by the arc is transmitted toward the bottom of wellbore **116**. When the shock wave hits and bounces off of the rock at the bottom of wellbore **116**, the rock fractures. Accordingly, drilling system **100** may utilize pulsed-power technology with an electrohydraulic drill bit to drill wellbore **116** in subterranean formation **118** in a similar manner as with electrocrushing drill bit **114**.

FIG. **2**A is a perspective view of exemplary components of the bottom-hole assembly for downhole electrocrushing drilling system **100**. BHA **128** may include pulsed-power tool **230**. BHA **128** may also include electrocrushing drill bit **114**. For the purposes of the present disclosure, electrocrushing drill bit **114** may be integrated within BHA **128**, or may be a separate component that is coupled to BHA **128**.

Pulsed-power tool **230** may provide pulsed electrical energy to electrocrushing drill bit **114**. Pulsed-power tool **230** receives electrical power from a power source via cable **220**. For example, pulsed-power tool **230** may receive electrical power via cable **220** from a power source located on the surface as described above with reference to FIG. **1**, or from a power source located downhole such as a generator powered by a mud turbine. Pulsed-power tool **230** may also receive electrical power via a combination of a power source located on the surface and a power source located downhole. Pulsed-power tool **230** converts electrical power received from the power source into high-energy electrical pulses that are applied across electrodes **208** and ground ring **250** of electrocrushing drill bit **114**. Pulsed-power tool **230** may also apply high-energy electrical pulses across electrode **210** and ground ring **250** in a similar manner as described herein for electrode **208** and ground ring **250**. To generate high-energy electrical pulses, pulsed-power tool **230** may include a pulse-generating circuit as described below with reference to FIG. **3**.

Referring to FIG. **1** and FIG. **2**A, electrocrushing drilling fluid **122** may exit drill string **108** via openings **209** surrounding each electrode **208** and each electrode **210**. The flow of electrocrushing drill fluid **122** out of openings **209** allows electrodes **208** and **210** to be insulated by the electrocrushing drilling fluid. Electrocrushing drill bit **114** may include a solid insulator (not expressly shown in FIG. **1** or **2**A) surrounding electrodes **208** and **210** and one or more orifices (not expressly shown in FIG. **1** or **2**A) on the face of electrocrushing drill bit **114** through which electrocrushing drilling fluid **122** exits drill string **108**. Such orifices may be simple holes, or they may be nozzles or other shaped features. Because fines are not typically generated during electrocrushing drilling, as opposed to mechanical drilling, electrocrushing drilling fluid **122** may not need to exit the drill bit at as high a pressure as the drilling fluid in mechanical drilling. As a result, nozzles and other features used to increase drilling fluid pressure may not be needed. However, nozzles or other features to increase electrocrushing drilling fluid **122** pressure or to direct electrocrushing drilling fluid may be included for some uses.

Electrocrushing drilling fluid **122** is typically circulated through drilling system **100** at a flow rate sufficient to remove fractured rock from the vicinity of electrocrushing drill bit **114**. In addition, electrocrushing drilling fluid **122** may be under sufficient pressure at a location in wellbore **116**, particularly a location near a hydrocarbon, gas, water, or other deposit, to prevent a blowout.

In addition, electrocrushing drill bit **114** may include ground ring **250**, shown in part in FIG. **2**A. Ground ring **250** may function as an electrode. Although illustrated as a contiguous ring in FIG. **2**A, ground ring **250** may be non-contiguous discrete electrodes and/or implemented in different shapes. Electrodes **208** and **210** may be at least 0.4 inches (i.e., at least approximately 10 millimeters) apart from ground ring **250** at their closest spacing, at least 1 inch (i.e., at least approximately 25 millimeters) apart at their closest spacing, at least 1.5 inches (i.e., at least approximately 38 millimeters) apart at their closest spacing, or at least 2 inches (i.e., at least approximately 51 millimeters) apart at their closest spacing. If drilling system **100** experiences vaporization bubbles in electrocrushing drilling fluid **122** near electrocrushing drill bit **114**, the vaporization bubbles may have deleterious effects. For instance, vaporization bubbles near electrodes **208** or **210** may impede formation of the arc in the rock. Electrocrushing drilling fluid **122** may be circulated at a flow rate also sufficient to remove vaporization bubbles from the vicinity of electrocrushing drill bit **114**. Although not all electrocrushing drill bits **114** may have ground ring **250**, if it is present, it may contain passages **260** to permit the flow of electrocrushing drilling fluid **122** along with any fractured rock or bubbles away from electrodes **208** and **210** and uphole.

FIG. **2**B is another perspective view of exemplary components of a bottom-hole assembly for downhole electrocrushing drilling system **100**. BHA **128** and pulsed-power tool **230** may include the same features and functionalities discussed above in FIG. 2A. For example, electrocrushing drilling fluid **122** may exit drill string **108** via opening **213** surrounding electrode **212**. The flow of electrocrushing drill fluid **122** out of opening **213** allows electrode **212** to be insulated by the electrocrushing drilling fluid. While one electrode **212** is shown in FIG. 2B, electrocrushing drill bit **115** may include multiple electrodes **212**. Electrocrushing drill bit **115** may include solid insulator **210** surrounding electrode **212** and one or more orifices (not expressly shown in FIG. 2B) on the face of electrocrushing drill bit **115** through which electrocrushing drilling fluid **122** exits drill string **108**. Nozzles or other features to increase electrocrushing drilling fluid **122** pressure or to direct electrocrushing drilling fluid may be included for some uses. Additionally, the shape of solid insulator **210** may be selected to enhance the flow of electrocrushing drilling fluid **122** around the components of electrocrushing drill bit **115**.

Electrocrushing drill bit **115** may include bit body **255**, electrode **212**, ground ring **250**, and solid insulator **210**. Electrode **212** may be placed approximately in the center of electrocrushing drill bit **115**. The distance between electrode **212** and ground ring **250** may be generally symmetrical or may be asymmetrical such that the electric field surrounding the electrocrushing drill bit has a symmetrical or asymmetrical shape. The distance between electrode **212** and ground ring **250** allows electrocrushing drilling fluid **122** to flow between electrode **212** and ground ring **250** to remove vaporization bubbles from the drilling area.

Electrode **212** may have any suitable diameter based on the drilling operation. For example, electrode **212** may have a diameter between approximately two and ten inches (i.e., between approximately 51 and 254 millimeters). The diameter of the electrode may be based on the diameter of electrocrushing drill bit **115**.

Ground ring **250** may function as an electrode and provide a location on the electrocrushing drill bit where an arc may initiate and/or terminate. Ground ring **250** also provides one or more fluid flow ports **260** such that electrocrushing drilling fluids flow through fluid flow ports **260** carry fractured rock and vaporization bubbles away from the drilling area.

FIG. **3** is a schematic for an exemplary pulse-generating circuit for a downhole electrocrushing drilling system. Pulse-generating circuit **300** includes power source input **302**, input stage circuit **304**, transformer circuit **306**, and output stage circuit **308**.

As described above with reference to FIGS. **2**A and **2**B, pulse-generating circuit **300** receives electrical power from a power source located on the surface (for example, generator **140** described with reference to FIG. **1**) and/or a power source located downhole, such as a generator powered by a mud turbine or an alternator. For example, input terminals **310** and **311** of power source input **302** may receive an alternating input current from a low-voltage (for example, a peak voltage between approximately 1 kV to 15 kV) power source by way of a cable, such as cable **220** described above with respect to FIGS. **2**A and **2**B. Input stage circuit **304** receives power from power source input **302** and controls the power supplied to transformer circuit **306**. Transformer circuit **306** in turn transforms the low-voltage input into a high-voltage output that is used to create electrical pulses capable of applying at least 50 kV or between approximately 50 kV and 200 kV with a rise time of approximately 5 to 25 microseconds across electrodes **208** or **210** and ground ring **250** of electrocrushing drill bit **114** illustrated in FIG. **2**A or electrode **212** and ground ring **250** of electrocrushing drill bit **115** illustrated in FIG. **2**B. As described above with reference to FIGS. **1** and **2**, the high-energy electrical pulses at electrodes **208**, **210**, and **212** are utilized to drill wellbore **116** in subterranean formation **118**.

Input stage circuit **304** is electrically driven by power source input **302**. Input stage circuit **304** includes capacitor **312** and switching circuit **314** electrically coupled to power source input **302**. An alternating current is applied to input terminals **310** and **311** of power source input **302** that charges the plates of capacitor **312** such that capacitor **312** stores energy from power source input **302**. Switching circuit **314** controls the flow of current to transformer circuit **306**. Switching circuit **314** includes any suitable device to open and close the electrical path between capacitor **312** and transformer circuit **306**. For example, switching circuit **314** may include a mechanical switch, a solid-state switch, a magnetic switch, a gas switch, or any other type or combination of switches (for example, an assembly of switches arranged in parallel or in series) suitable to open and close the electrical path between capacitor **312** and inductor **316**. When switching circuit **314** is closed, electrical current flows from capacitor **312** and/or input terminals **310** and **311** to transformer circuit **306**. Thus, switching circuit **314** controls the timing of power pulses supplied to the input side of transformer circuit **306**. The current supplied to the input side of transformer circuit **306** may be between approximately 4 kA and 40 kA. Input stage circuit **304** may include one or more additional components (for example, a capacitor, resistor, and/or inductor) beyond those shown in FIG. **3** to condition or control power from power source input **302** before it is supplied to transformer circuit **306**.

Transformer circuit **306** includes primary windings **316** and secondary windings **318** configured as a voltage step-up transformer. For example, primary windings **316**, windings electrically coupled to input stage circuit **304** on the input or primary side, may be wound around the same core as secondary windings **318**, windings electrically coupled to output stage **308** on the output or secondary side, to form an electrical transformer. Current from input stage circuit **304** flowing through primary windings **316** creates electromagnetism that induces a current through secondary windings **318** on the secondary side of transformer circuit **306**. As described in more detail below with respect to FIGS. **4**A and **4**B, transformer circuit **306** may be an open-core, multi-segmented transformer that steps up or increases the voltage on the secondary side of pulse-generating circuit **300**. For example, transformer circuit **306** may transform a low-voltage (for example, approximately 1 kV to 15 kV) from power source input **302** into a high voltage of at least 50 kV or between approximately 50 kV and 200 kV that is capable of creating high-energy electrical pulses to perform electrocrushing and/or electrohydraulic drilling. The open-core, multi-segmented design of transformer circuit **306** allows pulse-generating circuit **300** to fit within a bottom-hole assembly (for example, BHA **128** discussed above with respect to FIGS. **1** and **2**) and generate high-energy pulses to perform electrocrushing and/or electrohydraulic drilling with a drill bit (for example, drill bits **114** and **115** discussed above with respect to FIGS. **2**A and **2**B).

Output stage circuit **308** stores energy from transformer circuit **306** to apply to the electrodes of an electrocrushing and/or electrohydraulic drill bit. Capacitor **320** is coupled to transformer circuit **306** such that it stores energy from the increased voltage generated on the secondary or output side of transformer circuit **306**. Electrode **208** and ground ring **250** are coupled to opposing terminals of capacitor **320** of output stage circuit **308**. Accordingly, as the electric potential across capacitor **320** increases, the electric potential across electrode **208** and ground ring **250** also increases. Electrode **208** and ground ring **250** are part of electrocrushing drill bit **114** described above with reference to FIGS. **1** and **2**A. When the electric potential across, for example, electrode **208** and ground ring **250** of an electrocrushing drill bit becomes sufficiently large, an electrical arc forms through a rock formation that is near electrode **208** and ground ring **250**. The arc provides a temporary electrical short between electrode **208** and ground ring **250**, and thus allows electric current to flow through the arc inside a portion of the rock formation at the bottom of wellbore. As described above with reference to FIG. **1**, the arc increases the temperature of the portion of the rock formation through which the arc flows and the surrounding formation and materials. The temperature is sufficiently high to vaporize any water or other fluids that might be touching or near the arc and may also vaporize part of the rock itself. The vaporization process creates a high-pressure gas which expands and, in turn, fractures the surrounding rock.

Although FIG. **3** is a schematic for a particular pulse-generating circuit topology, electrocrushing and/or electrohydraulic drilling systems and pulsed-power tools may utilize any suitable pulse-generating circuit topology to generate and apply high-energy pulses to electrode **208** and ground ring **250**. These pulse-generating circuit topologies may utilize a voltage step-up transformer to generate a high voltage that is used to create high-energy electrical pulses required for electrocrushing and/or electrohydraulic drilling. Elements may be added or removed from the schematic illustrated in FIG. **3** without deviating from the present invention. For example, additional elements may be added to input stage circuit **304** to condition the power from power source input **302** before it is supplied to transformer circuit **306**. Although electrode **208** and ground ring **250** are shown in FIG. **3**, pulse-generating circuit **300** may supply high-energy electrical pulses to other electrodes, such as **208** or **210** and ground ring **250** of electrocrushing drill bit **114** or electrode **212** and ground ring **250** of electrocrushing drill bit **115** respectively described above with reference to FIGS. **2**A and **2**B. The individual circuit elements in pulse-generating circuit **300** may be selected based on the operating characteristics, such as voltage, current, and/or frequency, of power source input **302**, and/or the on the desired performance of the drill bit and/or pulse-generating circuit. For example, when power source input **302** operates at a frequency of 5 kilohertz (kHz), a combined primary current between approximately 4 kA and 40 kA, and a voltage between approximately 1 kV and 15 kV, capacitor **312** may have a value between 4 microfarad (uF) and 2 millifarad (mF), and capacitor **320** may have a value between 70 nanofarad (nF) and 150 nF. The design and configuration of transformer circuit **306** is discussed in more detail below with regard to FIGS. **4** and **4**A.

FIG. **4**A is a side cross-sectional view of an exemplary transformer circuit for a downhole electrocrushing and/or electrohydraulic drilling system, and FIG. **4**B is an exploded view of the same. Transformer circuit **306** is voltage step-up transformer that includes primary windings **316** and secondary windings **318** around core **406** within housing **410**. Primary windings **316** are comprised of multiple wires segments configured concentrically with secondary windings **318** to form an open-core transformer that operates in the manner described below. Insulating material **412** may be placed between primary windings **316** and secondary windings **318** to electrically isolate the windings and prevent electrical shorts between the wires in the windings. Insulating material **412** may include any electrically insulating materials, including those discussed below with respect to FIG. **5**.

Multi-segmented primary windings **316** are formed of individual wire segments wrapped around core **406**. The wire segments of primary windings **316** may be placed side-by-side along the length of core **406**. The segmented wires of multi-segmented primary windings **316** are coupled to a common power source, such as power source input **302** of FIG. **3** via an input circuit, such as input stage circuit **304** of FIG. **3**. As described above with reference to FIG. **3**, an alternating current from the power source input flows through primary windings **316** such that the current creates a variable electromagnetism (i.e., magnetic flux) in and around secondary windings **318**. Primary windings **316** include electrically conductive material, such as copper, formed in a solid or hollow shape with a circular or rectangular cross section. Although primary windings **316** are shown configured as a solenoid in FIGS. **4**A and **4**B, primary windings **316** may be configured in another arrangement around **406**.

Secondary windings **318** of transformer circuit **306** also wrap around core **406** to form transformer circuit **306** with primary windings **316**. Primary windings **316** are wrapped around secondary windings **318** and core **406** such that windings **316** and **318** are concentric relative to each other. Electromagnetism created by the flow of current in primary windings **316** induces current and voltage in secondary windings **318** due to electromagnetic induction. The current and voltage created in secondary windings **318** powers other elements, such as output stage circuit **308** of pulse-generating circuit **300** described above with respect to FIG. **3**. Secondary windings **318** include electrically conductive material, such as copper, formed in a solid or hollow shape having a circular or rectangular cross section. Although secondary windings **318** are shown as being located within primary windings **316** in FIG. **4**A, secondary windings **318** may wrap around primary windings **316** and core **406** such that windings **316** and **318** are concentric relative to each other. Secondary windings **318** may be configured in another arrangement around **406** other than the solenoid configuration illustrated in FIG. **4**A.

Primary windings **316** and secondary windings **318** are configured to form a step-up transformer that transforms the low input voltage into a higher output voltage. The output voltage of transformer circuit **306** depends in part on the ratio of windings between primary windings **316** and secondary windings **318**. Secondary windings **318** include a higher number of windings as compared to the total number of windings in primary windings **316**. For example, secondary windings **318** may include between approximately 8 to 12 or more times as many windings as compared to primary windings **316**. The higher ratio of secondary windings **318** to primary windings **316** transforms the low input voltage supplied by the power source on the primary side of transformer circuit **306** into a higher output voltage on the secondary side of transformer circuit **306**. The increase of output voltage on the secondary side as compared to the input voltage on the primary side is approximately proportionate to the ratio of primary windings **316** to secondary windings **318**. Thus, the ratio of secondary windings **318** to primary windings **316** enables transformer circuit **306** to transform the low voltage (for example, approximately 1 kV to 15 kV) from the power source input into an output voltage of at least 50 kV or between approximately 50 kV and 200 kV. The higher output voltage can be discharged in approximately 5 to 25 microseconds to create the high-energy pulses used for electrocrushing drilling. To enable a higher turn ratio, primary windings **316** may be formed of more wire segments having fewer turns, or secondary windings **318** may be located concentrically within primary windings **316** such that more secondary windings may be placed in a smaller area using minimal electrically conductive material.

The individual wires of primary windings **316** form a multi-segmented primary winding. Current from power source input flows through each wire segment of primary windings **316**. Each wire segment has an electrical impedance that opposes the flow of current through the wire and varies based on the material, length, resistance, capacitance and/or other attributes of the wire. The wire segments of primary windings **316** are connected in parallel to a common power source input (for example, power source input **302** of FIG. **3**) via an input circuit, such as input stage circuit **304** of FIG. **3**. By arranging wires in parallel, the combined impedance for primary windings **316** is reduced such that more current (for example, between approximately 4 kA and 40 kA) may be supplied to primary windings **316** as compared to a transformer with non-segmented primary windings due to the reduced opposition to current flow in the wires. The increased current in primary windings **316** enables a higher operating power in addition to creating increased electromagnetism that enables a higher output voltage of transformer circuit **306**. In addition, the reduced impedance of primary windings **316** reduces the amount of heat generated by the operation of transformer circuit **306**, thereby reducing the operational energy loss and improving the energy transfer efficiency of the circuit as compared to a transformer circuit with non-segmented primary windings. Thus, multi-segmented primary windings **316** increase the operating power range and improve the efficiency of transformer circuit **306**.

Transformer circuit **306** is designed as an open-core transformer to reduce the diameter of the pulse-generating circuit **300**. In a closed-core transformer, the core material is formed in a ring to concentrate electromagnetism between the windings. By contrast, an open-core transformer, such as transformer circuit **306** with core **406**, is formed of an elongated shape with a narrow cross-section (for example, a cylinder with a diameter between approximately 2 and 24 inches or 5 and 61 centimeters) such that transformer circuit **306** fits within a bottom-hole assembly (for example, BHA **128** discussed above with respect to FIGS. **1** and **2**) of a drill bit (for example, drill bits **114** and **115** discussed above with respect to FIGS. **2**A and **2**B) utilized to drill a wellbore in a subterranean formation. Accordingly, the open-core design enables a smaller diameter for transformer circuit **306** that facilitates downhole placement.

An open-core design may result in decreased electromagnetic coupling between primary windings **316** and secondary windings **318** as compared to a closed-core design. Thus, the placement of primary windings **316** and secondary windings **318** is selected to enhance the electromagnetic coupling between the windings. Primary windings **316** are wrapped around secondary windings **318** in a concentric manner. As explained above, electromagnetism created by the flow of current in primary windings **316** induces current and voltage in secondary windings **318** due to electromagnetic induction. Some electromagnetism created on the primary side is lost due to materials near and the spacing between windings **316** and **318**. To reduce this loss, windings **316** and **318** may be placed in close proximity to each other (for example, approximately 3 and 20 millimeters apart) to increase the electromagnetic coupling between the windings. The electromagnetic coupling may be expressed as a coupling coefficient, a fractional number between 0 and 1, where a lower coupling coefficient represents a smaller electromagnetic coupling and a higher coupling coefficient represents a higher electromagnetic coupling. The higher the coupling coefficient, the higher the induced current and voltage in secondary windings **318**. The placement of windings **316** and **318** within transformer circuit **306** may achieve a coupling coefficient between approximately 0.4 and 0.8. Increasing the electromagnetic coupling between primary windings **316** and secondary windings **318** may reduce the electromagnetic loss between the windings and thereby improve the operating efficiency of transformer circuit **306**. The close proximity between windings **316** and **318** may also help maintain a diameter for transformer circuit **306** that fits within a bottom-hole assembly (for example, BHA **128** discussed above with respect to FIGS. **1** and **2**).

Transformer circuit **306** may be an open-core, air-core transformer that includes no added magnetic material. That is, the space between windings **316** and **318** may be filled with air or other non-ferromagnetic materials such that transformer circuit **306** is an air-core design. The air-core design of transformer circuit **306** helps avoid saturation common with magnetic core material and variability caused by the effect of extreme downhole operating conditions on the performance of core material.

Core **406** of transformer circuit **306** is located at or near the center of concentric windings **316** and **318**. Primary windings **316** wrap around secondary windings **318**, and both windings wrap around core **406**. Due to its placement outside (not between the windings) of concentric windings, core **406** is not part of the magnetic circuit formed between primary windings **316** and secondary windings **318**. Core **406** still affects the electromagnetic coupling between windings **316** and **318** because of its proximity and placement relative to the windings. For example, core **406** may concentrate fringe magnetic flux (i.e., fringe electromagnetism that is outside of the magnetic circuit formed between primary windings **316** and secondary windings **318**) along the internal diameter of transformer circuit **306**. Concentrating fringe magnetic flux near the center of transformer circuit **306** may reduce the amount of fringe magnetic flux that is lost as the flux intercepts and dissipates through other downhole components. Reducing flux in other downhole components may improve the electromagnetic coupling between windings **316** and **318**, and thus the operating efficiency of transformer circuit **306**. Similar to the space between primary windings **316** and secondary windings **318** discussed above, core **406** may be filled with air or other non-ferromagnetic material. However, core **406** may also include supplemental magnetic core material to help attract fringe magnetic flux along the internal diameter of transformer circuit **306**. The chances of saturation for magnetic material within core **406** are eliminated because core **406** experiences less electromagnetic flux than the magnetic circuit between primary windings **316** and secondary windings **318**, and the electromagnetic flux is not stored in the open-core configuration. The supplemental core added to core **406** may be selected to have lower variability in response to the extreme downhole operating conditions. For example, preferred supplemental core material includes a cobalt-iron alloy such as supermendur, which may include approximately forty-eight percent cobalt, approximately forty-eight percent iron, and approximately two percent vanadium by weight. The supermendur material maintains its high relative permeability across a wide range of temperatures (for example, from approximately 10 to 200 degrees Centigrade), and thus withstands the high temperatures of a downhole environment. The supplemental core material may also include a ferrite material, a strip laminate magnetic material with a Curie temperature 200 degrees Centigrade or greater, Metglas®, which includes a thin amorphous metal alloy ribbon which may be magnetized and demagnetized, or other high magnetic permeability material that maintains its magnetic permeability across a range of downhole temperatures (for example, from approximately 10 to 200 degrees Centigrade) such as Silectron™ (for example, silicon steel material composed of approximately 3% silicon steel and 97% iron) and Supermalloy™ (for example, composed of approximately 80% Nickel-Iron and approximately 20% iron alloy).

The various design features of transformer circuit **306** enable the circuit to operate at a high-power level while still physically fitting within the narrow confines of a wellbore. For example, multi-segmented primary windings **316** help reduce the impedance on the input side of transformer circuit **306** such that more input current can flow through the circuit. The multi-segmented primary windings **316** simultaneously reduce operational energy loss, thereby improving the operating efficiency of the circuit. A higher ratio of secondary windings **318** to primary windings **316** steps up the low input voltage to a higher output voltage that is used to generate high-energy pulses for electrocrushing or electrohydraulic drilling. Transformer circuit **306** may be configured with a narrow diameter due to its open-core design with concentric primary and secondary windings. The air-core design of transformer circuit **306** eliminates the risk of saturation common with magnetic core material and variability caused by the effect of extreme downhole operating conditions on the performance of the core material. Supplemental magnetic core material may be added to core **406**, outside of the magnetic circuit of the transformer, to concentrate the fringe magnetic flux away from other downhole components, thereby reducing fringe magnetic flux loss and the operating efficiency of transformer circuit **306**.

Transformer circuit **306** may be physically sized to fit in a downhole tool. The physical size of transformer circuit **306** may depend on the size of core **406**, the number and size of primary windings **316** and secondary windings **318**, the spacing between primary windings **316** and secondary windings **318**, the dimensions of housing **410**, and the arrangement and/or spacing of primary windings **316** and secondary windings **318** within housing **410**. The length (along the X axis in FIG. **4**A) of transformer circuit **306** may vary inversely with the width (along the Y axis of FIG. **4**A) of transformer circuit **306**. As transformer circuit **306** is made narrower to fit within wellbores with smaller diameters, the length of pulse-generating circuit **300** may increase to accommodate the materials and components comprising the circuit. Conversely, the length of pulse-generating circuit **300** may be decreased by increasing the width of pulse-generating circuit **300**. The length of transformer circuit **306** may be between approximately 3 and 25 feet (between approximately 1 and 8 meters) and the diameter of the circuit may be between approximately 4 and 20 inches (between approximately 10 and 51 centimeters).

Pulse-generating circuit **300** may be encapsulated by insulating material to protect against the harsh downhole environment and facilitate dissipation of heat generated by the circuit. FIG. **5** is a top cross-sectional view of an exemplary pulsed-power tool for a downhole electrocrushing and/or electrohydraulic drilling system. Pulsed-power tool **230** includes pulse-generating circuit **300**, the circuit depicted above in FIG. **3**. Pulse-generating circuit **300** may be shaped and sized to fit within the circular cross-section of pulsed-power tool **230**, which as described above with reference to FIGS. **2**A and **2**B, may form part of BHA **128**. Pulse-generating circuit **300** may be enclosed within encapsulant **510** that includes a thermally conductive material to protect pulse-generating circuit **300** from the wide range of temperatures (for example, from approximately 10 to 200 degrees Centigrade) within the wellbore. For example, encapsulant **510** may include APTEK® 2100-A/B, which is a two-component, unfilled, electrically insulating urethane system for the potting and encapsulation of electronic components, and has a thermal conductivity of approximately 170 mW/mK. Encapsulant **510** may include one or more other thermally conductive materials with a dielectric strength greater than approximately 350 volt/mil (for example, greater than approximately 13,780 volt/millimeter) and a temperature capability greater than approximately 120 degrees Centigrade, such as DOW CORNING® OE-6636 and OE-6550, and Kapton® polyimide film. Encapsulant **510** adjoins an outer wall of one or more fluid channels **234**. As described above with reference to FIG. **1**, drilling fluid **122** passes through interior channels (for example, fluid channels **234**) of drill string **108** as drilling fluid is pumped down through a drill string. Encapsulant **510** may transfer heat generated by pulse-generating circuit **300** to the drilling fluid that passes through fluid channels **234**. Encapsulant **510** may also insulate pulse-generating circuit **300** from heat generated by other downhole components. Thus, encapsulant **510** may prevent pulse-generating circuit **300** from overheating to a temperature that degrades the relative permeability of core of the cores of the inductors in pulse-generating circuit **500**.

FIG. **6** illustrates a flow chart of exemplary method for drilling a wellbore.

Method **600** may begin and at step **610** an electrocrushing or electrohydraulic drill bit may be placed downhole in a wellbore. For example, drill bit **114** may be placed downhole in wellbore **116** as shown in FIG. **1**.

At step **620**, electrical energy is provided to a pulse-generating circuit coupled to a first electrode and a second electrode of the drill bit. The first electrode may be electrode **208**, **210**, or **212** and the second electrode may be ground ring **250** discussed above with respect to FIGS. **2**A and **2**B. For example, as described above with reference to FIG. **3**, pulse-generating circuit **300** may be implemented within pulsed-power tool **230** of FIGS. **2**A and **2**B. And as described above with reference to FIGS. **2**A and **2**B, pulsed-power tool **230** may receive electrical power from a power source on the surface, from a power source located downhole, or from a combination of a power source on the surface and a power source located downhole. Power may be supplied downhole to pulse-generating circuit **300** by way of a cable, such as cable **220** described above with respect to FIGS. **2**A and **2**B. The power may be provided to pulse-generating circuit **300** within pulse-power tool **230** at power source input **302**.

At step **630**, the pulse-generating circuit converts the electrical power from the power source into high-energy electrical pulses for use of the electrocrushing drill bit. For example, as described above with reference to FIG. **3**, pulse-generating circuit **300** may include an input stage circuit **304**, transformer circuit **306**, and an output stage circuit **308**. Pulse-generating circuit **300** steps up the low-voltage input to a high-voltage output that is used to create high-energy pulses for the drilling system. For example, the pulse-generating circuit may use a higher ratio of secondary windings to primary windings in the transformer circuit to convert a low-voltage power source input (for example, approximately 1 kV to 15 kV) into high-energy electrical pulses capable of applying at least 50 kV or between approximately 50 kV and 200 kV across electrodes of the drill bit.

At step **640**, an electrical arc may be formed between two electrodes of the drill bit. For example, an electrical arc may be formed between electrode **208** or **210** and ground ring **250** of electrocrushing drill bit **114** illustrated in FIG. **2**A or electrode **212** and ground ring **250** of electrocrushing drill bit **115** illustrated in FIG. **2**B.

And at step **650**, a capacitor in output stage circuit may discharge via the electrical arc. For example, as the voltage across capacitor **320** of output stage circuit **308** increases during step **630**, the voltage across the first electrode and the second electrode also increases. As described above with reference to FIGS. **1** and **2**, when the voltage across the two electrodes (for example, electrode **208** and ground ring **250** illustrated in FIG. **3**) becomes sufficiently large, an arc may form through a rock formation that is in contact with or near the electrodes. The arc may provide a temporary electrical short between electrode **208** and ground ring **250**, and thus may discharge, at a high current level, the voltage built up across capacitor **320** illustrated in FIG. **3**.

At step **660**, the rock formation at an end of the wellbore may be fractured with the electrical arc. For example, as described above with reference to FIGS. **1** and **2**, the arc greatly increases the temperature of the portion of the rock formation through which the arc flows as well as the surrounding formation and materials. The temperature is sufficiently high to vaporize any water or other fluids that may be touching or near the arc and may also vaporize part of the rock itself. The vaporization process creates a high-pressure gas which expands and, in turn, fractures the surrounding rock.

At step **670**, fractured rock may be removed from the end of the wellbore. For example, as described above with reference to FIG. **1**, electrocrushing drilling fluid **122** may move the fractured rock away from the electrodes and uphole away from the drill bit. As described above with respect to FIGS. **2**A and **2**B, electrocrushing drilling fluid **122** and the fractured rock may pass away from electrodes through passages **260** in the drill bit. Subsequently, method **700** may end.

Modifications, additions, or omissions may be made to method **700** without departing from the scope of the disclosure. For example, the order of the steps may be performed in a different manner than that described and some steps may be performed at the same time. Additionally, each individual step may include additional steps without departing from the scope of the present disclosure.

Embodiments herein may include:

A. A downhole drilling system including a pulse-generating circuit electrically coupled to a power source configured to provide an alternating current at a frequency and an input voltage, the pulse-generating circuit comprising an input stage circuit electrically coupled to the power source, the input stage circuit configured to control the alternating current in the pulse-generating circuit; a transformer circuit electrically coupled to the input stage circuit, the transformer circuit comprising an open-core transformer configured to generate an output voltage higher than the input voltage; and an output stage circuit electrically coupled to the transformer circuit, the output stage circuit configured to store energy for an electric pulse; and a drill bit including a first electrode and a second electrode electrically coupled to the output stage circuit to receive the electric pulse from the pulse-generating circuit.

B. A method including providing an alternating current and an input voltage from a power source at a frequency to a pulse-generating circuit electrically coupled to a drill bit located downhole in a wellbore; generating an electric pulse with the pulse-generating circuit, the electric pulse stored in an output capacitor and generated at the frequency by an open-core transformer, forming an electrical arc between a first electrode and a second electrode of the drill bit, the first electrode and the second electrode electrically coupled to the output capacitor; discharging the output capacitor by the electrical arc; fracturing a rock formation at an end of the wellbore with the electrical arc; and removing fractured rock from the end of the wellbore.

Each of embodiments A and B may have one or more of the following additional elements in any combination: Element 1: wherein the input stage circuit comprises a capacitor; and a switch coupled to the capacitor, the switch configured to open and close an electrical path between the capacitor and the transformer circuit, the alternating current from the power source passing to the transformer circuit when the electrical path is closed. Element 2: wherein the transformer circuit further comprises a plurality of primary windings electrically coupled to the input stage circuit; and a plurality of secondary windings concentric to and electromagnetically coupled to the primary windings, the primary and secondary windings forming the open-core transformer. Element 3: wherein the open-core transformer is further configured as an air-core transformer having no ferromagnetic material. Element 4: wherein the primary windings are comprised of a plurality of segmented wires coupled to the input stage circuit. Element 5: wherein the primary and secondary windings are wound around a core. Element 6: wherein the core concentrates a fringe magnetic flux of the primary and secondary windings. Element 7: wherein the frequency is less than 100 MHz. Element 8: wherein the electric pulse from the pulse-generating circuit applies a voltage of at least 50 kV across the two electrodes. Element 9: wherein the drill bit is integrated within a bottom-hole assembly. Element 10: wherein the drill bit is one of an electrocrushing drill bit and an electrohydraulic drill bit. Element 11: wherein one of the two electrodes is a ground ring. Element 12: wherein the pulse-generating circuit comprises an input stage circuit electrically coupled to the power source, the input stage circuit configured to control the alternating current in the pulse-generating circuit; a transformer circuit electrically coupled to the input stage circuit, the transformer circuit comprising the open-core transformer configured to generate an output voltage higher than the input voltage with the voltage step-up transformer; and an output stage circuit electrically coupled to the transformer circuit, the output stage circuit configured to store an energy from the output voltage.

The embodiments described in the present disclosure are intended for use in electrocrushing and/or electrohydraulic drilling, and reference to one or the other form of drilling in the above disclosure is not intended to limit the applicability of the embodiment to that particular form of drilling. Although the present disclosure has been described with several embodiments, various changes and modifications may be suggested to one skilled in the art. It is intended that the present disclosure encompasses such various changes and modifications as falling within the scope of the appended claims.

What is claimed is:

**1**. A downhole drilling system, comprising:

a bottom hole assembly within a wellbore configured to receive drilling fluid from a drill string;

a pulse-generating circuit within the bottom hole assembly and electrically coupled to a power source configured to provide an alternating current at a frequency and an input voltage, the pulse-generating circuit comprising:
an input stage circuit electrically coupled to the power source, the input stage circuit configured to control the alternating current in the pulse-generating circuit;
a transformer circuit electrically coupled to the input stage circuit, the transformer circuit comprising an open-core transformer configured to generate an output voltage higher than the input voltage and allow drilling fluid to flow through the open-core transformer; and
an output stage circuit electrically coupled to the transformer circuit, the output stage circuit configured to store energy for an electric pulse; and
a drill bit including a first electrode and a second electrode electrically coupled to the output stage circuit to receive the electric pulse from the pulse-generating circuit.

**2**. The downhole drilling system of claim **1**, wherein the input stage circuit comprises:
a capacitor; and
a switch coupled to the capacitor, the switch configured to open and close an electrical path between the capacitor and the transformer circuit, the alternating current from the power source passing to the transformer circuit when the electrical path is closed.

**3**. The downhole drilling system of claim **1**, wherein the transformer circuit further comprises:
a plurality of primary windings electrically coupled to the input stage circuit; and
a plurality of secondary windings concentric to and electromagnetically coupled to the primary windings, the primary and secondary windings forming the open-core transformer.

**4**. The downhole drilling system of claim **3**, wherein the open-core transformer is further configured as an air-core transformer having no ferromagnetic material.

**5**. The downhole drilling system of claim **3**, wherein the primary windings are comprised of a plurality of segmented wires coupled to the input stage circuit.

**6**. The downhole drilling system of claim **3**, wherein the primary and secondary windings are wound around a core.

**7**. The downhole drilling system of claim **6**, wherein the core concentrates a fringe magnetic flux of the primary and secondary windings.

**8**. The downhole drilling system of claim **1**, wherein the frequency is less than 100 MHz.

**9**. The downhole drilling system of claim **1**, wherein the electric pulse from the pulse-generating circuit applies a voltage of at least 50 kV across the two electrodes.

**10**. The downhole drilling system of claim **1**, wherein the drill bit is one of an electrocrushing drill bit and an electrohydraulic drill bit.

**11**. The downhole drilling system of claim **1**, wherein one of the two electrodes is a ground ring.

**12**. A method, comprising:
receiving drilling fluid at a bottom hole assembly within a wellbore;
providing an alternating current and an input voltage from a power source at a frequency to a pulse-generating circuit electrically coupled to a drill bit located downhole in a wellbore;
generating an electric pulse with the pulse-generating circuit within the bottom hole assembly and, the electric pulse stored in an output capacitor and generated at the frequency by an open-core transformer, wherein the pulse-generating circuit comprises:
an input stage circuit electrically coupled to the power source, the input stage circuit configured to control the alternating current in the pulse-generating circuit;
a transformer circuit electrically coupled to the input stage circuit, the transformer circuit comprising the open-core transformer configured to generate an output voltage higher than the input voltage and allow drilling fluid to flow through the open-core transformer; and
an output stage circuit electrically coupled to the transformer circuit, the output stage circuit configured to store an energy from the output voltage;
forming an electrical arc between a first electrode and a second electrode of the drill bit, the first electrode and the second electrode electrically coupled to the output capacitor;
discharging the output capacitor by the electrical arc;
fracturing a rock formation at an end of the wellbore with the electrical arc; and
removing fractured rock from the end of the wellbore.

**13**. The method of claim **12**, wherein the input stage circuit comprises:
a capacitor; and
a switch coupled to the capacitor, the switch configured to open and close an electrical path between the capacitor and the transformer circuit, the alternating current from the power source passing to the transformer circuit when the electrical path is closed.

**14**. The method of claim **12**, wherein the transformer circuit comprises:
a plurality of primary windings electrically coupled to the input stage circuit; and
a plurality of secondary windings concentric to and electromagnetically coupled to the primary windings, the primary and secondary windings forming the open-core transformer.

**15**. The method of claim **14**, wherein the primary windings are comprised of a plurality of segmented wires coupled to the input stage circuit.

**16**. The method of claim **14**, wherein the primary and secondary windings are wound around a core.

**17**. The method of claim **16**, wherein the core concentrates a fringe magnetic flux of the primary and secondary windings.

**18**. The method of claim **12**, wherein the frequency is less than 100 MHz.

**19**. The method of claim **12**, wherein the electric pulse from the pulse-generating circuit applies a voltage of at least 50 kV across the first electrode and the second electrode.

**20**. The method of claim **12**, wherein the drill bit is one of an electrocrushing drill bit and an electrohydraulic drill bit.

**21**. The method of claim **12**, wherein one of the first and second electrode is a ground ring.

* * * * *